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LCA FOR ENERGY SYSTEMS

Life cycle assessment of electricity transmission and distribution—part 2: transformers and substation equipment

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Abstract
Purpose The purpose of this paper is to characterize the environmental impacts of equipment used in power transmission and distribution. This study is divided in two parts, each addressing different main components of the electrical grid system. This part is concerned with the impacts of transformers and substation equipment while in part 1 a similar analysis is presented for power lines and cables.
Methods The method used here is process-based life cycle assessment. Ecoinvent v 2.2 is used as a background dataset, and the results are obtained with the impact assessment method ReCiPe Midpoint Hierarchist perspective (v1.0). The average European power mix is used to model the electrical energy required to compensate power losses in the electrical equipment.
Results and discussion Assuming a European power mix, results for transformers indicate that power losses are by far the most dominant process for almost all impact categories evaluated here, contributing at least 96% to climate change impacts. An exception is the category of metal depletion, for which production of raw materials is the most relevant process. Within infrastructure-related impacts, the production of raw materials is the most important process. Recycling shows benefits for most impact categories. For some substation equipment using sulfur hexafluoride (SF_6), climate change impacts due to SF_6 leakages surpass impacts due to losses.
Conclusions The results suggest that improvements in component efficiency—reduction of power losses and reduction of SF_6 gas leakages in gas-insulated equipment—would significantly contribute to decreases in overall component impacts.

Keywords Electricity transmission · Environmental impacts of energy systems · Life cycle assessment · Substation equipment · Transformers

1 Introduction

This article was motivated by the idea of compiling life cycle inventories and life cycle assessment (LCA) data for the main components of electrical grids. Such inventories not only serve the purpose of providing data and results for the individual components studied, but they can also be useful in further LCA studies where there is a need to model a customized grid connection—for example, for an offshore wind power plant—by assembling the different components into a grid system. Following part 1, here, we present an LCA analysis for power transformers and other equipment used in substations. Electrical grid components generate impacts in each of the following life cycle stages: raw materials production, raw materials transportation, manufacturing, final product transportation, installation, use

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(power losses and maintenance), and end-of-life. This analysis aims at calculating total environmental scores for transformers and substation equipment and also to identify relevant processes for each impact category studied. We expect that over the lifetime, power losses will be an important contributor especially for the impacts of transformers, while for equipment using sulphur hexafluoride (SF_6), leakages in manufacturing, use, and dismantling of the equipment are expected to have a significant contribution. Here, the electrical energy required to compensate power losses in the equipment is modeled as the average European power mix (Ecoinvent 2007b). The leakages of SF_6 are modeled as direct emissions to air and the additional production of gas to compensate for gas mass loss is also included here.

2 Methods and data

2.1 Scope and functional unit

This LCA study addresses impacts for transformers and equipment used in substations, e.g., switchgear. Table 1 provides a list of all the components modeled. Inventory data for transformers and substation equipment were compiled from the environmental product declarations available at ABB (2003a, b, c, d, e, f, g, h; 2002a, b; 2004; 2011a, b, c, d, e, f) and from a technical report for transformers which was obtained from the manufacturer unit at Monselice (ABB 2003a). Detailed life cycle inventories for all components, including data on all modeled processes, equipment power losses, and lifetime are provided in the Supplemental Information section. The functional unit for transformers is one device operating during the lifetime. For switchgear, the functional unit is 1 unit of a gas-insulated substation (GIS). A typical 300-kV GIS consists of 5 to 7 units, and a typical GIS rated at 420 kV consists of 8 to 12 functional units, according to (ABB 2003h; 2011b). For the other components, the functional unit is one device operational during the lifetime.

2.2 LCA model details

Similarly to part 1, the method used here is process-based LCA (Rebitzer et al. 2004), and the impact assessment method is ReCiPe Midpoint Hierarchist Perspective v1.0 (Goedkoop et al. 2009). Ecoinvent v 2.2 (Ecoinvent Centre 2007a) is used to model the background system processes. The included processes are the following: power losses, raw materials production, transportation, use/maintenance, and end of life. Resources use/direct emissions from manufacturing are available from ABB (2003a) and are therefore included for transformers. For the transformers, total power losses are given by the sum of load losses and no-load losses. Load losses in transformers are associated with the coils and vary according with the loading on the transformer. To model load losses in the transformers analysed here, we assume a 50% average load scenario, same as in ABB (2003a). No-load losses occur due to magnetization current needed to energize the core of the transformer. No-load losses are constant and do not depend on the transformer load. For an equipment using SF_6 gas as insulation material, it is estimated that a fraction of the gas will leak during manufacturing, use, and dismantling. The inventories in the Supplemental Information section have data on these leakages for each phase, but typically in the use phase, it is estimated that around 0.1% of the gas is lost per year. The leakages in these components are modeled as SF_6 emissions to air (Ecoinvent Centre 2007a) and we also account for the extra SF_6 gas that needs to be produced to compensate for the leakage. To model end of life of transformers, the procedure followed is the one indicated at ABB (2003a). According to this source, metal parts (copper, steel, and aluminum) are recycled. The recycling rate for the metal parts is 90%. The remaining 10% are assumed to go to landfill. Transformer oil should be

Table 1 Electrical grid components included in the model

LCA model components: transformers and substation equipment	
Distribution transformer 315 kVA	Gas-insulated switchgear 300 kV
Large distribution transformer 9.6 MVA	Gas-insulated switchgear 420 kV
Large distribution transformer 16 MVA	Plug and switch system
Large distribution transformer 20 MVA	Double breaker disconnector
Power transformer 40 MVA	Center breaker disconnector
Power transformer 50 MVA	Power generator circuit breaker
Power transformer 63 MVA	Live tank circuit breaker
Power transformer 250 MVA	Uniswitch
Power transformer 500 MVA	Surge arrester

LCA life cycle assessment

disposed according to local regulations. To model this, the Ecoinvent unit process used was disposal of mineral oil, which assumes incineration. For all the components, the end of life scenarios include processes such as landfill, incineration, and recycling. To account for the benefits and costs of recycling, the same procedure as in Ecoinvent was used here. To model recycling of steel, for example, pig iron is used as avoided production and iron scrap is used as an input from the technosphere.

2.3 LCI data quality and representativeness

The life cycle inventory (LCI) data for transformers and other substation equipment are based on data from the manufacturer, ABB, which is a global supplier of this type of equipment. To model material production (steel, copper, etc.), we have chosen processes from the Ecoinvent database v 2.2 (Ecoinvent Centre 2007a) representing European production. Power losses in the equipment are modeled as the average European power production mix (Ecoinvent 2007b). The results will therefore reflect this modeling context.

3 Results

3.1 Transformers

Total life cycle environmental scores for transformer for the selected impact categories are presented in Table 2. These scores represent the sum of impacts for all life cycle stages of the transformers, i.e., raw materials production, manufacturing, transportation, power losses, maintenance, and end of life processes. Under the assumption of European electricity mix, a transformer rated at 500 MVA could contribute with up to 90 ktonCO_2-eq to climate change during its lifetime. Furthermore, it was investigated how much power losses contribute to the total environmental scores. As expected, a large share of the total life cycle impacts of transformers is attributed to this process. Table 3 provides the values for electricity loss in each transformer as a percentage of the total electricity flowing in the device. The table also shows the contribution of both load losses and no-load losses for the total global warming potential (GWP) 100. Although power losses are less than 1% of the total electricity flowing in the transformer at each time, over the lifetime, they represent a significant sum. Load losses contribute to at least 66% of the total value of GWP 100, while no-load losses are responsible for at least 16% of the total climate change for all transformers. Total (load + no-load) power losses in transformers are also by far the largest contributor for other impact categories (see Table S19, Electronic Supplementary Material). The category of metal depletion is an exception. Here, the process of raw materials production has a higher contribution, while total power losses contribute with between 35% and 62% to total climate impacts. After the losses, which make up the largest share of impacts, there are other processes, related to infrastructure, which also contribute to the total environmental score of the components. These processes are the following: production of raw materials, manufacturing, transportation, maintenance, and end of life. Figure 1 shows the breakdown of impacts due to these

Table 2 Life cycle environmental impacts for transformers

Impact category (unit)	Transformer rating (MVA)								
	0.315	10	16	20	40	50	63	250	500
Climate change (kton CO_2-eq)	0.27	4.61	6.20	8.50	16.22	21.90	23.86	51.62	88.23
Fossil depletion (kton oil-eq)	0.08	1.36	1.84	2.51	4.79	6.46	7.04	15.24	26.03
Freshwater ecotoxicity (kton 1,4-DCB-eq)	<0.01	0.06	0.08	0.11	0.20	0.27	0.30	0.65	1.11
Freshwater eutrofication (ton P-eq)	0.22	3.83	5.16	7.10	13.56	18.37	20.11	43.09	74.08
Human toxicity (kton 1,4-DCB-eq)	0.15	2.61	3.54	4.83	9.14	12.32	13.68	29.01	50.08
Marine eutrophication (ton N-eq)	0.27	4.66	6.26	8.59	16.39	22.16	24.20	52.12	89.34
Metal depletion (ton Fe-eq)	0.01	0.17	0.26	0.27	0.42	0.45	0.61	1.27	2.05
Ozone depletion (kg CFC-11-eq)	0.01	0.23	0.31	0.42	0.80	1.07	1.17	2.55	4.34
Particulate matter formation (ton PM10-eq)	0.36	6.14	8.28	11.21	21.27	28.51	32.10	67.58	117.57
Photochemical oxidant formation (ton NMVOC)	0.59	10.17	13.75	18.54	35.07	46.92	51.91	111.44	190.73
Terrestrial acidification (ton SO_2-eq)	1.09	18.44	24.83	33.93	64.65	87.18	99.36	205.41	362.43
Terrestrial ecotoxicity (ton 1,4-DCB-eq)	0.03	0.52	0.70	0.95	1.79	2.40	2.67	5.70	9.81

NMVOC non-methane volatile organic compound

Table 3 Percentage energy loss in transformers and contribution of load losses and no-load losses for transformer GWP 100

Transformer rating (MVA)	Energy losses (%)[a]	Contribution to GWP 100[b]	
		Load losses (%)	No-load losses (%)
0.315	0.97	68	29
9.6	0.52	71	26
16	0.44	66	30
20	0.48	75	22
40	0.46	79	19
50	0.50	84	14
63	0.43	84	14
250	0.24	74	24
500	0.20	82	16

GWP global warming potential

[a]As percent of total electricity flow in the transformer

[b]As percent of total GWP 100

processes. The *x*-axis in Fig. 1 represents the value of the total score for each impact category, for each infrastructure life cycle stage, while the *y*-axis indicates the transformer rating. Figure 1 shows that within infrastructure-related impacts, the production of raw materials is the most important contributor for all categories. After that, transportation is relevant for climate change, fossil depletion, ozone depletion, and terrestrial ecotoxicity. Manufacturing has a smaller contribution than raw materials production and transportation for all impact categories. Negative scores for end-of-life occur when the recycling benefits outweigh the impacts caused by landfill and other disposal processes. One process that was found to generate high end of life impacts for transformers, particularly for climate change, was disposal of used transformer oil. This is why the end-of-life scores for climate change are close to zero because the benefits of recycling are not high enough to compensate for the impacts of other end-of-life processes. But for other impact categories, e.g., toxicity or metal depletion, it is clear that the benefits of recycling are larger. The impacts of maintenance are negligible compared to the other phases and due to the very small share this process is only visible in the plot for the 500-MVA transformer, in the category of terrestrial ecotoxicity. This is because the only maintenance operation required for transformers is a single application of paint once per lifetime, which is modeled here as paint production only. Transformer oil is also filtered once per lifetime, but that operation is not modeled here because of lack of data for that process.

3.2 Substation equipment

Total life cycle environmental scores for substation equipment components in the different impact categories are presented in Table 4. The scores represent the sum of impacts generated in each of the life cycle stages modeled for this type of equipment: raw materials production, transportation, use, SF_6 losses (for the equipment using this gas as insulation), and end of life processes. As for the transformers, we have also investigated how much power losses contribute to total life cycle climate change scores. The results are presented in Table 5. The contribution of power losses to GWP 100 for the switchgear and the plug and switch system is under 20%, a value which is much lower than the one obtained for the transformers. For the circuit breakers and disconnectors, power losses contribute at least 78% to the total GWP 100. It was also investigated how much SF_6 leakages contribute to the total GWP 100. SF_6 losses, which were modeled as emissions to air, are found to be the largest contributor to GWP 100 for the switchgear and plug and switch system, with a share of at least 72% of the total GWP 100 score. Figure 2a, b shows the breakdown of impacts related to all the processes excluding power losses, i.e., for raw materials production, transportation, use phase, SF_6 losses, and end of life. In Fig. 2a, the results are presented for the equipment with largest environmental scores, i.e., the switchgear at 300 and 420 kV, the plug and switch system, and the power generator circuit breaker. In Fig. 2b, similar results are presented for the double breaker disconnector, the live tank circuit breaker, the double breaker disconnector, and medium voltage switchgear—Uniswitch. The component names are indicated by their abbreviations. The plots show that materials production is the largest contributor to all the impact categories, with exception of climate change, where SF_6 losses can be the dominate process. In fact, the SF_6 losses contribute exclusively to climate change impacts. For some components, transportation is a relevant process in climate change, fossil depletion, ozone depletion, terrestrial ecotoxicity, and terrestrial acidification. For the Switchgear at 300 and 420 kV, the use phase has a significant share of impacts in fossil depletion and ozone depletion, and also some

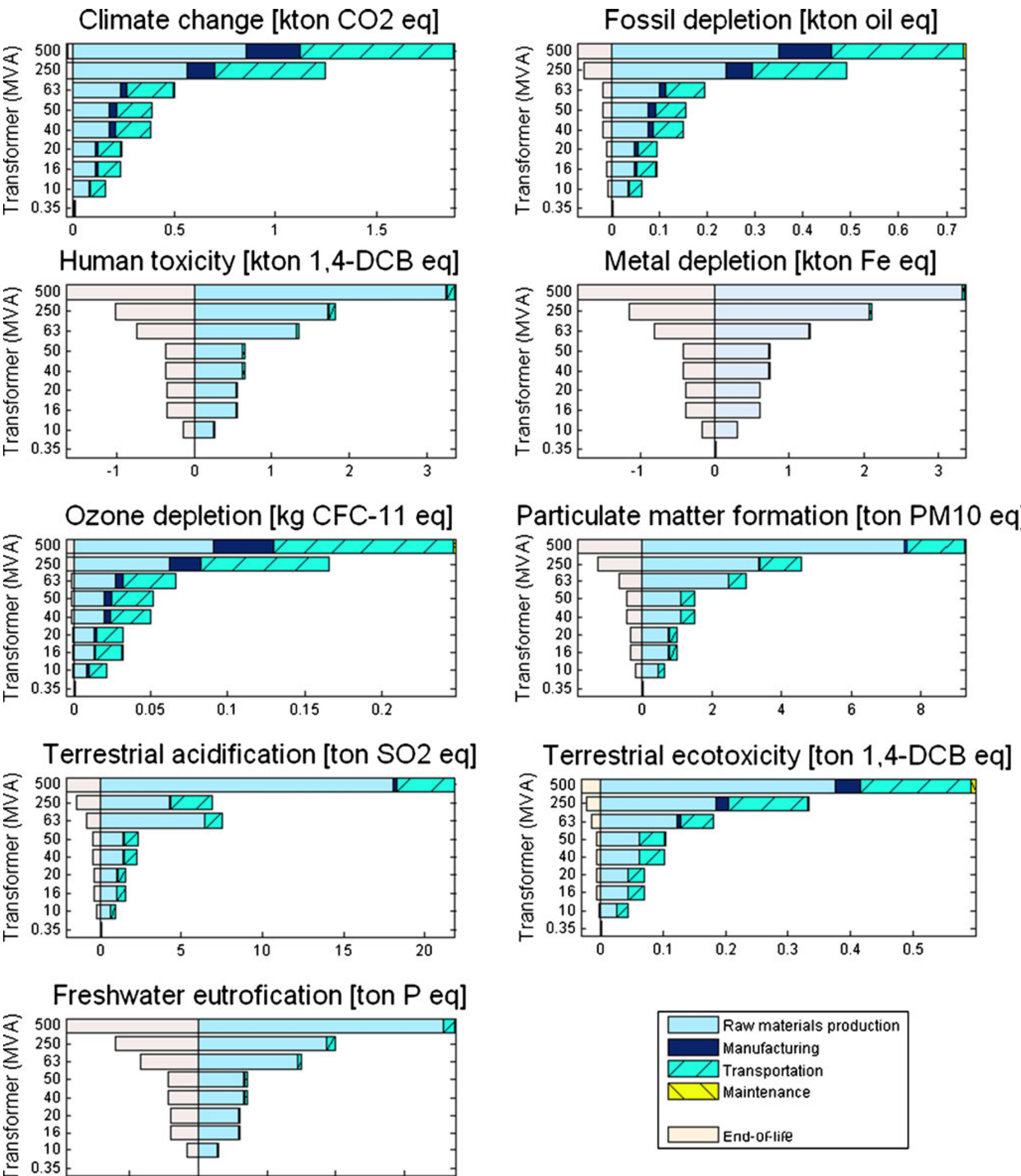

Fig. 1 Breakdown of impacts associated with infrastructure for transformers

impact in climate change. Switchgear requires heat in the use phase, which contributes to these impacts. The benefits of recycling are larger for this type of equipment then for the transformers. This is because transformers use transformer oil, and treatment (disposal) of the oil at the end of life is a process which generates high impacts.

Table 4 Life cycle environmental impacts for substation equipment

Impact category (unit)	G.I.S. 300 kV	G.I.S. 420 kV	Plug and switch	D.B. disc.	C.B. disc.	Power G.C.B	L.T.C.B.	Uniswitch	Surge arrester
Climate change (ton CO_2-eq)	286.46	930.30	204.84	35.97	25.86	114.27	69.62	0.80	0.03
Fossil depletion (ton oil-eq)	21.78	49.65	12.14	10.73	7.94	28.72	19.06	0.19	0.01
Freshwater ecotoxicity (ton 1,4-DCB-eq)	1.00	2.54	0.63	0.66	0.43	1.64	1.05	0.03	<0.01
Freshwater eutrofication (kg P-eq)	26.48	108.38	31.94	27.52	20.24	80.61	59.62	0.22	0.02
Human toxicity (ton 1,4-DCB-eq)	30.25	93.09	25.68	21.05	14.82	59.85	51.02	0.49	0.02
Marine eutrophication (kg N-eq)	40.58	137.25	40.34	35.63	25.75	98.05	66.53	0.48	0.03
Metal depletion (ton Fe-eq)	18.75	27.05	4.26	5.98	3.13	9.72	5.95	0.67	<0.01
Ozone depletion (g CFC-11-eq)	6.33	10.89	2.29	2.11	1.53	5.09	3.30	0.06	<0.01
Particulate matter formation (kg PM10-eq)	105.89	289.81	63.31	66.29	43.79	151.33	99.30	2.20	0.06
Photochemical oxidant formation (kg NMVOC)	188.53	425.76	108.09	95.68	66.85	228.18	149.43	2.80	0.12
Terrestrial acidification (kg SO2-eq)	234.79	823.62	177.24	153.43	108.77	438.78	275.32	3.25	0.15
Terrestrial ecotoxicity (kg 1,4-DCB-eq)	7.89	18.81	5.18	4.76	3.29	12.14	7.56	0.15	0.01

G.I.S. gas-insulated switchgear, *D.B. disc* double breaker disconnector. *C.B. disc* center breaker disconnector, *G.C.B.* generator circuit breaker, *L.T. C.B.* live tank circuit breaker

4 Uncertainty and limitations

Matching processes from the inventories with the ones available at the database used (Ecoinvent) is possible for most materials and processes modeled, but as expected, there are limitations. For example, transformer oil is modeled as lubricating oil, since that was the closest match available. For substation equipment using SF_6 as insulation material, the production of extra SF_6 to compensate for leakages is included, as well as direct emissions of the gas to air. However, recycling of SF_6 at the end of life was not included, since the process is not part of the Ecoinvent v 2.2 database.

Table 5 Contribution of power losses and SF_6 losses to total GWP 100 of substation equipment

	Contribution to GWP 100[a]	
	Power losses (%)	SF6 losses (%)
G.I. switchgear 300 kV	6	72
G.I. switchgear 420 kV	11	76
Plug and switch system	17	78
D.B. disconnector	83	–
C.B. disconnector	87	–
P.G. circuit breaker	78	10
L.T. circuit breaker	85	7
M.V. switchgear	–	24
Surge arrester	39	–

GWP global warming potential, *G.I.* gas insulated, *D.B.* double breaker, *C.B.* circuit breaker, *P.G.* power generator, *L.T.* live tank, *M. V.* medium voltage

[a] As percent of total GWP 100

5 Conclusions and recommendations

We have compiled life cycle inventories for a variety of equipment used in electricity transmission and distribution. Environmental scores were analyzed with the recently released ReCiPe impact assessment method. For transformers, the results show that power losses dominate the impacts for most components in most impact categories. This suggests that improvements in component efficiency would be important in lowering the impacts of this equipment. Nevertheless, making the equipment more efficient would perhaps also require higher material and energy inputs for their construction. The environmental trade-off between higher efficiency and material/energy use is an interesting aspect to address in further energy systems studies and in grid planning. For substation equipment using SF_6 gas as insulation material, leakages of this gas represent up to 78% of the total GWP 100 score. The inventories compiled here offer several advantages: it is possible to model the impacts of individual power grid components, while it is also possible to assemble the different devices to model a specific system, for example, the grid connection for an offshore wind farm, and then calculate the resultant impacts for that system. Although the LCIs are based on specific conditions, power losses are provided separately, so region-specific electricity mixes can easily be substituted.

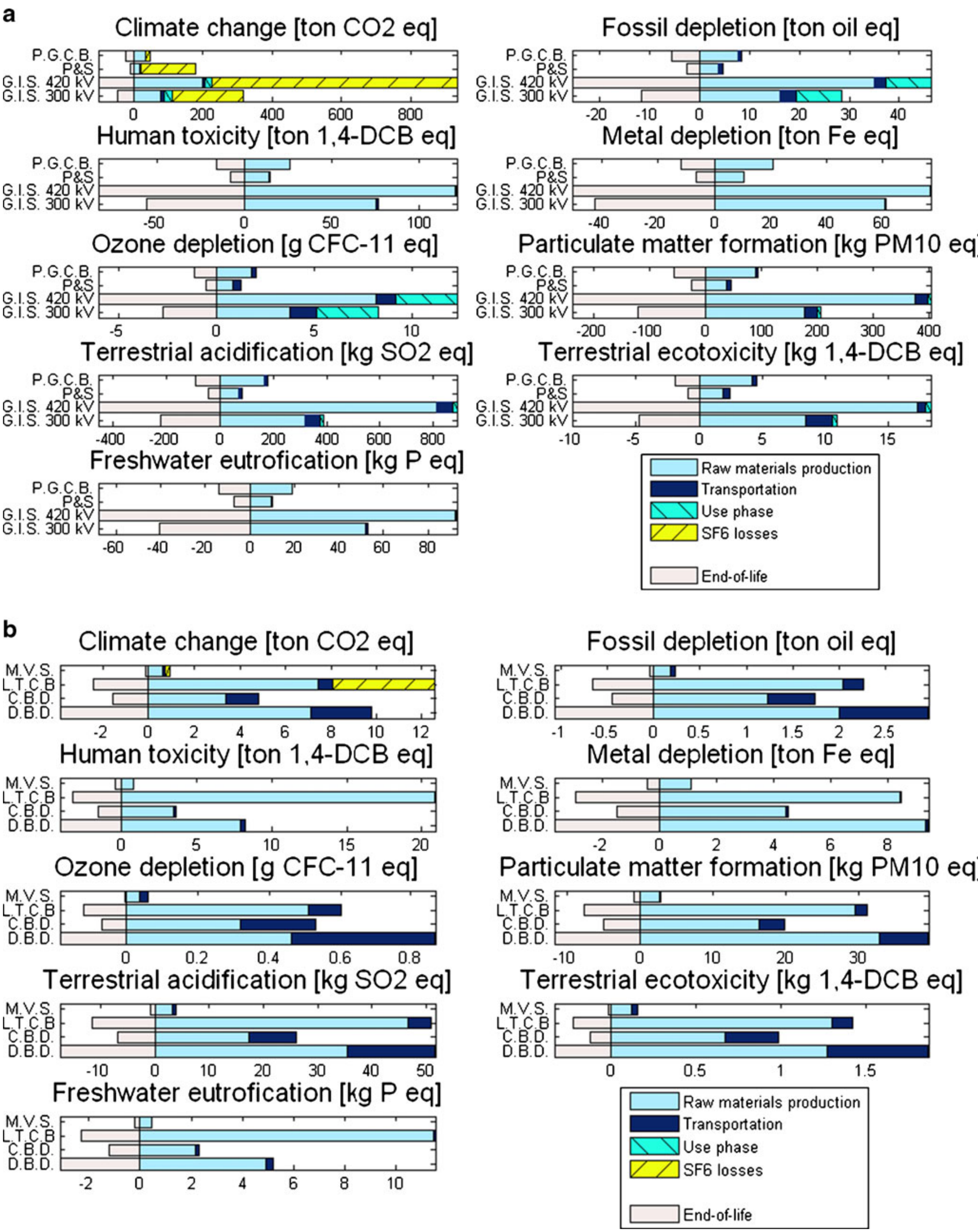

Fig. 2 Breakdown of impacts associated with infrastructure and SF_6 losses for substation equipment. **a** Impacts for switchgears, plug and switch system, and power generator circuit breaker. **b** Impacts for double breaker disconnector, circuit breaker disconnector, live tank circuit breaker, and medium-voltage switchgear (Uniswitch)

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